REPORT DOCUMENTATIC

AD-A258 472

Public reporting burden for this collection of information is estimated to average 1 hour p·
maintaining the data needed, and completing and reviewing the collection of information. Ser
for reducing this burden, to Washington Headquarters Services, Directorate for informatic
the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Wash

lata sources, gathering and
ation, including suggestions
ton, VA 22202-4302, and to

1. Agency Use Only *(Leave blank)*.	2. Report Date. October 1992	3. Report Type and Dates Covered. Final - Proceedings	

4. Title and Subtitle. A Study of Pulse Scattering in a Waveguide	5. Funding Numbers. *Contract*

	Program Element No.	0601153N

6. Author(s).
Michael K. Broadhead, Michael F. Werby, and Hassan B. Ali

Project No.	03202
Task No.	340
Accession No.	DN255011
Work Unit No.	12212B

7. Performing Organization Name(s) and Address(es).
Naval Research Laboratory
Ocean Acoustics and Technology Directorate
Stennis Space Center, MS 39529-5004

DTIC
ELECTE
DEC 9 1992
S C D

**8. Performing Organization
Report Number.**

PR 92:036:244

9. Sponsoring/Monitoring Agency Name(s) and Address(es).
Naval Research Laboratory
Ocean Acoustics and Technology Directorate
Stennis Space Center, MS 39529-5004

**10. Sponsoring/Monitoring Agency
Report Number.**

PR 92:036:244

11. Supplementary Notes.
Published in Proceedings of Mastering the Oceans Through Technology, (OCEANS 92).

12a. Distribution/Availability Statement. Approved for public release; distribution is unlimited.	12b. Distribution Code.

13. Abstract *(Maximum 200 words)*.

The problem of the scattering of a continuous acoustic wave (CW) from a submerged object in a waveguide has received extensive treatment in the frequency domain, where phenomena associated with the resonant behavior of the object have been studied in detail. This paper concentrates on the time-domain interpretation of the scattering problem. Computation of the scattered field from an incident pulse, which requires calculations for many frequencies, is performed using a new perturbation technique (computed to all orders that allows rapid calculation of the waveguide modes. An implementation of the inverse Fourier transform is presented that is more appropriate to resonance-type spectra. The computational tools developed are used to elucidate various physical aspects of pulse scattering in a waveguide, including: group velocity behavior, direct modal contributions, and resonance contributions from individually excited modes.

14. Subject Terms. Acoustic scattering, shallow water, waveguide propagation	15. Number of Pages. 4
	16. Price Code.

17. Security Classification of Report. Unclassified	18. Security Classification of This Page. Unclassified	19. Security Classification of Abstract. Unclassified	20. Limitation of Abstract. SAR

DTIC QU̶A̶.̶ ̶ ̶.̶.̶.̶.̶ ̶.̶.̶.̶J̶I̶E̶D̶ 2

A Study of Pulse Scattering in a Waveguide

Michael K. Broadhead, Michael F. Werby, and Hassan B. Ali

Naval Research Laboratory, Stennis Space Center, MS 39529-5004

Abstract – The problem of the scattering of a continuous acoustic wave (CW) from a submerged object in a waveguide has received extensive treatment in the frequency domain, where phenomena associated with the resonant behavior of the object have been studied in detail. This paper concentrates on the time-domain interpretation of the scattering problem. Computation of the scattered field from an incident pulse, which requires calculations for many frequencies, is performed using a new perturbation technique (computed to all orders) that allows rapid calculation of the waveguide modes. An implementation of the inverse Fourier transform is presented that is more appropriate to resonance-type spectra. The computational tools developed are used to elucidate various physical aspects of pulse scattering in a waveguide, including: group velocity behavior, direct modal contributions, and resonance contributions from individually excited modes.

1. INTRODUCTION

The frequency domain treatment of acoustic scattering from objects in a bounded medium such as an ocean waveguide has received extensive study [1]. It is our purpose in this paper to present results on extending this work to the time domain. The essential steps in the process are to 1) calculate the single-frequency incident pressure field, 2) compute the scattered field off an object of interest and 3) repeat the calculations for many frequencies and synthesize the scattered field by Fourier integrating the results into a time domain response. This is physically equivalent to transmitting and scattering a pulse off the target.

To accomplish the above, we compute the incident pressure field in the ocean waveguide using a new perturbative approach to normal modes [2]. The modes provide a set of orthogonal basis functions in which to expand the incident single-frequency field. We then use the T-Matrix method to couple the incident field to the scattered field. If this calculation is repeated for a number of frequencies, an inverse Fourier transformation of the complex pressure field will produce a time domain scattered field. By reconstructing only certain combinations of modes, or individual modes, we can break up the time domain response into various modal contributions. We can also produce pulses for various frequency ranges. The ability to manipulate the frequencies and modes allow us to decompose the time domain response (which can be very complicated) into its constituents, thereby elucidating the physical mechanisms of the different arrivals. This should be especially useful in the case of resonance scattering from elastic targets.

Previous work has been done on the time domain calculation of scattering from unbounded elastic objects [3]. Our goal is to extend this to elastic objects in a waveguide. Since we already have the T-Matrix codes necessary to compute the scattered expansion coefficients, the additional tools we require are a way to calculate normal modes rapidly, yet accurately, and a numerical method for accurately evaluating the inverse Fourier transform when resonance effects are important. In this paper we will report on progress we have made in developing these tools, with primary emphasis on the normal mode calculations. We have developed a new perturbation method that allows rapid, accurate calculation of the normal modes from which the complex pressure field can be computed [2]. The new perturbation method allows us to write the perturbed normal modes as a linear combination of sine functions, which is important in allowing us to expand the incident field into a spherical representation for coupling to the T-matrix.

In the following sections we will present the basics of the T-Matrix approach to scattering, the extension of this technique to the time domain, the basic ideas behind the new perturbative approach to normal modes, a new frequency integration method, and some first-order results illustrating the kinds of quantities we can compute.

2. EXTENDING THE T-MATRIX TO TIME DOMAIN

The basic reference for the following material is Werby [4]. In this section we will review the methods by which the waveguide pressure field is coupled to the scattered near field from the target. The Extended Boundary Condition method [5] (or T-matrix) transforms the incident field into the scattered near field. The incident field is expanded into a spherical representation, where the expansion coefficients are represented by the column vector a. The T-matrix transforms a into f, the expansion coefficients for the scattered near field, or;

$$f = T\,a . \qquad (1)$$

To couple the scattered field into the waveguide, we use Huygen's principle;

$$U_s(r) = \int (p(r')\partial G(r,r')/\partial n$$

$$- G(r,r')\partial f(r')/\partial n)dS , \qquad (2)$$

where p is the nearfield scattered pressure obtained from f [4]. The calculated pressure field is represented by the Green's function G. If we compute G by normal modes, we can write;

$$G = (i/2d) \sum \phi_n \left(\gamma_n z_s\right) \phi_n \left(\gamma_n z\right) H_0 \left(\kappa_n r\right) , \quad (3)$$

where H_0 is an outgoing cylindrical Hankel function and ϕ_n, γ_n and κ_n are the normal mode functions and the vertical and horizontal eigenvalues, respectively.

Before we leave this section, we should discuss the method we use for frequency integration. The inverse Fourier transform over a complex field $F(\omega)$ can be written;

$$f(t) = \frac{1}{2\pi} \int_{-}^{+-} F(\omega) e^{i\omega t} d\omega . \quad (4)$$

We could use an FFT, or a traditional numerical integration scheme, but we will present here a way that is more suited to our needs in scattering. For some small $\Delta\omega$, we can write $f(t)$ to a good approximation as,

$$f(t) = \frac{1}{2\pi} \sum_n \int_{\omega_n - \Delta\omega}^{\omega_n + \Delta\omega} F(\omega) e^{i\omega t} d\omega . \quad (5)$$

If we can assume that $F(\omega)$ doesn't change much over any particular interval, we can bring $F(\omega_n)$ out of the integral and analytically evaluate what is left to get

$$f(t) = \frac{1}{\pi} \sum_n \frac{\sin(\Delta\omega_n t)}{t} F(\omega_n) e^{i\omega_n t} . \quad (6)$$

We index $\Delta\omega$ to allow for the possibility of a nonuniform grid spacing. A similar formulation was published by Bracewell [6]. We have added an interpolation (Newton's method) step as well, although it is not always needed. This formulation is useful since we can accurately compute cases where the pressure field exhibits resonance effects by concentrating the grid in their vicinity.

3. NEW PERTURBATION APPROACH TO NORMAL MODES

The use of normal modes in ocean acoustics is extensively documented. See, for example, Boyles [7]. The heart of the problem is to solve the depth equation. The unperturbed depth equation can be written as

$$\frac{d^2}{dz^2} \psi_i + \left[k_0^2 - \lambda_i^{(0)}\right] \psi_i = 0 , \text{ where} \quad (7)$$

λ_i^0 are the horizontal wave numbers, ψ_i are the modal amplitudes from which the pressure field can be computed, and $k_0 = \frac{\omega}{c_0}$.

If we let the perturbation $-q(z)$ be added, we have

$$\frac{d^2}{dz^2} U_i + \left[k^2(z) - \lambda_i\right] U_i = 0, \quad (8)$$

where U_i are the perturbed normal modes, and $k^2(z) = k_0^2 - q(z)$. Using completeness, we assume the following solution form;

$$U_i = \sum_{j=1}^{N} a_{ij} \psi_i \quad (9)$$

In [2] it is shown that this leads to the following expression for the eigenvalues;

$$\lambda_i = \lambda_i^{(0)} - q_{ii} - \sum_{i \neq j}^{N} \tilde{a}_{ij} q_{ij} , \quad (10)$$

where $\tilde{a}_{ij} \equiv \dfrac{a_{ij}}{a_{ii}}$, and $q_{ij} \equiv \int \psi_i^* q(z) \psi_j \, dz$. $\quad (11)$

To obtain the new normal modes U_i, we solve the following linear system;

$$\tilde{a}_{ik} \left(\alpha_i^2 - \alpha_k^2 + H_{ik}\right) - \sum_{j \neq \{i,k\}}^{N} q_{jk} \tilde{a}_{ij} = q_{ik} , \quad (12)$$

where $k = 1, 2, \cdots, N; i \neq k$,

$$H_{ik} = q_{kk} - \Delta\lambda_i ,$$

$$\Delta\lambda_i = \lambda_i - \lambda_i^0 ,$$

and $\quad \alpha_i^2 = k_0^2 - \lambda_i^{(0)}$. $\quad (13)$

Nowhere do these expressions involve an approximation by truncating an expansion, as does traditional perturbation theory. Accuracy benchmark runs vs SUPERSNAP so far indicate near perfect reconstruction of the modes for the cases we have tried. Although we haven't benchmarked computer run time yet, our subjective impression is that the algorithm is very fast. For the unperturbed case, we use an isovelocity profile over a half space. These normal modes are just sine

478

functions, and the q_{ij} integrals can be done analytically. Bottom attenuation is included in the usual way, and we have plans to add 1) sediment layers, 2) an elastic bottom, and 3) extend the program to coupled modes.

4. DISCUSSION OF FIGURES

To illustrate the potential for synthesizing time domain solutions using the new method, we ran the program for the following case. We used a bilinear sound speed profile with z, c values of (0 m, 1510 m/s), (100 m, 1476 m/s), and (300 m, 1520 m/s). The water and sediment densities used were 1000 kg/m and 1600 kg/m³, and the sediment velocity was 1600 m/s. We used a frequency band of 10 to 150 Hz with a Δ = 0.5 Hz. The source and receiver depths were both 100 m and no bottom attenuation was included.

In Figure 1, we show the first arrival results for the above waveguide. Figure 1(a) is for range R = 10 km, and (b) is for R = 20 km. This shows the geometric dispersion effect in waveguides. Figure 2 (a-d) shows partial modal constructions for R = 10 km. Figure 2(a) is the time domain response for the single mode = 1, and 2(b) and (2c) are the single modes 2 and 3 respectively. Figure (4d) is the sum of the 3 modes and should be compared to Figure 1(a). Figure 3(a and b) are the phase and group velocities calculated for the first three modes.

5. CONCLUSIONS

We have presented all of the basic features of performing pulse scattering in a waveguide from elastic targets. Primary emphasis was on a new perturbation method for computing normal modes. This was useful in two ways: 1) The method is rapid, facilitating the calculation of many frequencies for synthesizing a pulse. 2) The perturbed solution can be written in terms of sine functions, facilitating the projection of the

incident field on to a spherical representation. We presented example calculations with this program to illustrate how we can decompose the time domain response according to modal arrivals.

7. REFERENCES

[1] M. F. Werby, Scattering from an object in a waveguide: some numerical examples, Computational Acoustic Scattering, Gaussian Beams, and Aeroacoustics, D. Lee, A. Cakmak, R. Vichnevetsky, Eds., North-Holland, 1990.

[2] M. F. Werby, R. A. Zingarelli, and M. K. Broadhead, A rapid expansion technique for the solution of a normal mode propagation model, Proc. Third IMACS Symp. on Computational Acous., Harvard U., June 1991.

[3] M. F. Werby and H. B. Ali, Time domain solution from the frequency domain: Application to resonance scattering from elastic bodies, Computational Acoustics: Scattering, Gaussian Beams, and Aeroacoustics, D. Lee, A. Cakmak, R. Vichnevetsky, Eds., North-Holland, 1990.

[4] M. F. Werby, Transient Solutions from scattered fields in a waveguide, Oceans '90 Conf. Proc., IEEE, New York, 1990.

[5] P. C. Waterman, New formulation of acoustic scattering, J. Acoust. Soc. Am., v. 45, p. 1417, 1969.

[6] R. N. Bracewell, The Fourier transform and its applications, 2nd Ed., McGraw-Hill, New York, 1978.

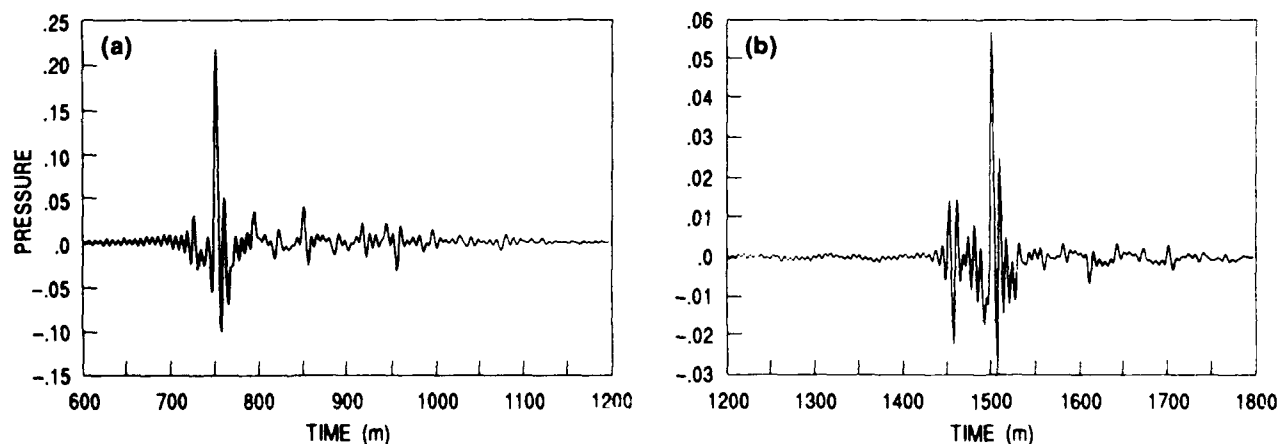[7] C. A. Boyles, Acoustic Waveguides: Applications to Oceanic Science, John Wiley and Sons, Inc., New York, 1984.

Figure 1. (a) Time domain first arrival solution for 10-150 Hz, R = 10 km, bilinear profile. (b) Same as (a), but R = 20 km.
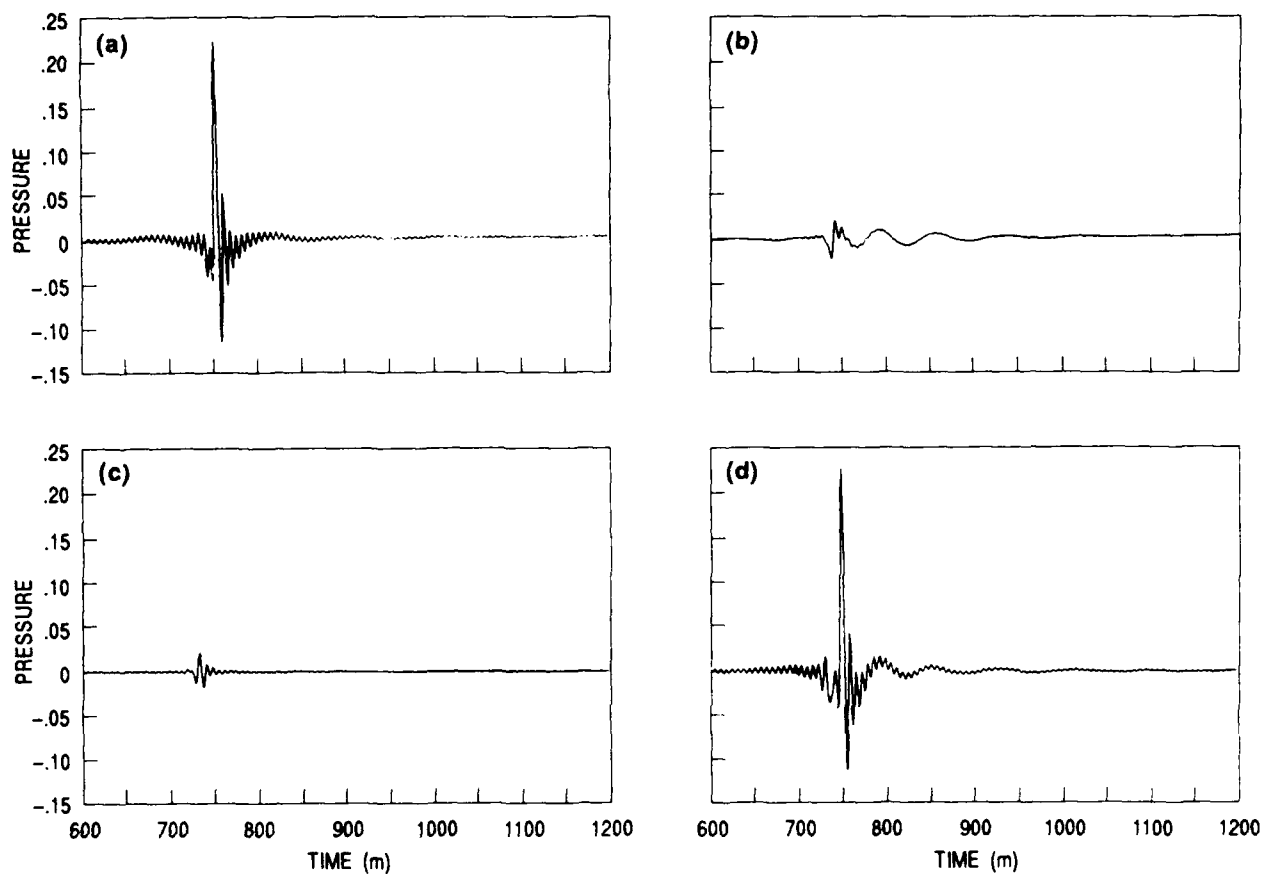
Figure 2. (a) Time domain response for single mode = 1. (b) Mode = 2. (c) Mode = 3. (d) Sum of first three modes.
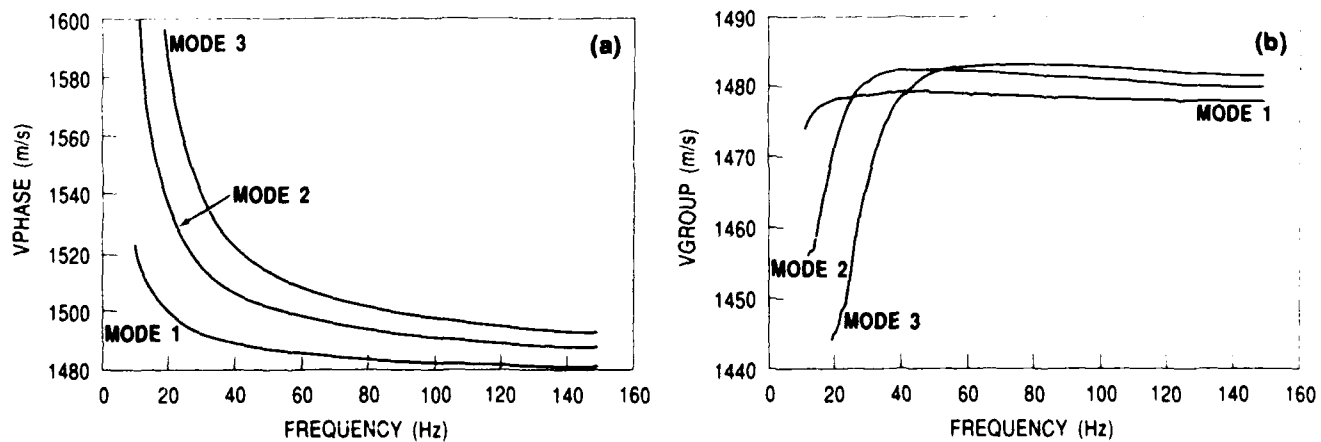

Figure 3. (a) Phase velocities for first three modes. (b) Group velocities for first three modes.